An Image-processing based Prototype of Decreasing Transmission Time of Visual Information for a Tele-operative Surgical System

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***Abstract* - The Internet-based tele-operative surgical training system for Vascular Interventional Surgery (VIS) is a promising method to protect surgeons from long time exposure to radiation and to do the surgery cooperatively across the whole world and to allow unskilled surgeons to learn basic catheter or guidewire skills corresponding to inter-country distances. However, unpredictable and variable transmission time of visual feedback is always accompanied by the significant deterioration of the feasibility and manoeuvrability and could lead to damage to tissues in actual surgery. In this paper, an image-processing based prototype was proposed to effectively reduce the transmission time of visual feedback. At patient's site, the shape of catheter or guidewire was detected in real time and the position of catheter was presented by the three dimensional coordinates in World Coordinate System (WCS). Furthermore, at operative site, the shape of catheter was reconstructed as the visual feedback according to the coordinate values received from patient's site. Transmission time of visual feedback was therefore decreased due to significant reduction of data volume. In addition, coordinates values are more easily synchronized with the control signals and haptic data due to the size between visual and other data is similar. Finally, a remote transmission experiment of visual feedback was conducted to show that the proposed prototype made a better performance improvement for Internet-based transmission with delays during inter-country distances.**

Index Terms - Vascular Interventional Surgery, image processing, a remote transmission experiment, transmission time, visual feedback

I. Introduction

Vascular Interventional Surgery (VIS) is a kind of minimally invasive therapy for cures of arterial aneurysm and other vascular disease [1]. During such a revolutionary surgical technique, surgeons are allowed to drive a catheter or guidewire inside patients' vascular structure from femoral artery to reach the target position to cure the vascular disease by manipulating the tail part of the catheter or guidewire. The main advantages of this surgical method are smaller incisions, less blood loss, decrease postoperative pain and a quicker recovery [2]. However, there are several problems related to the conventional way of performing this technology because it requires extensive training efforts of the surgeon to achieve the competency due to the fact that the vascular structure which the catheter passed through is highly brittle and complex. Thus distance teaching has become indispensable to novice surgeons across a country or the world [3]. In addition, when the emergency medical care happens, it is required that competent surgeons can work cooperatively to a surgery which takes place in another country [4]. Also, the surgeons could have prolonged exposure to radiation [5]-[6]. Therefore, a more precise, securer, and dependable prototype that can disseminate new surgical knowledge, skills and techniques across the whole world and reduce the radiation exposure to surgical doctors is urgent to be developed.

Aiming to meet these requirements, remote surgery is a promising method to realize participations of highly capable doctors to a surgery, which takes place in a distant place. Furthermore, it is possible to facilitate a team work medical treatment between doctors from all around the world [7]-[8]. Obviously, doctors can be protected from longtime radiation. Authors in [9] have performed a remote surgery based on a surgical robot named ZEUS in 2001 through a dedicated Asynchronous Transfer Mode (ATM) between New York and Strasbourg, France. Nevertheless, it is extremely expensive for laying such a kind of dedicated fiber-optic lines and conducting remote surgery based on them. Thus using the conventional network infrastructures such as Internet is more preferable for the future expansion of remote surgery applications [7].

Therefore, many research groups that have studied the robotic tele-surgical systems based on Internet [9]-[15]. Generally, the concept of Internet-based surgical system consists of three parts, a master system, a slave system and a communication link, as **Fig.**1 shows. Master system and slave system are connected by TCP/IP networks for sending and receiving data such as image information, force and control signals of manipulators.

Obviously, time delay of visual transmission is an unavoidable problem referring to this kind of Internet-based remote surgical systems. The size of visual information is much larger than control and force signals. Thus the incremental time delay of visual information is always accompanied by the significant deterioration of the feasibility and maneuverability and could lead to damage to tissues in actual surgery and training effect during remote surgical education. Currently, researchers mainly focused on delayed control and force signals through the Internet, nevertheless few academic

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institutions are engaged in the time delay of visual transmission. Traditionally, delays of visual information have been coped with predictive methods or through increased autonomy [16] or a high speed image compression process [8]. However, these methods are a little time consuming and complex to perform.

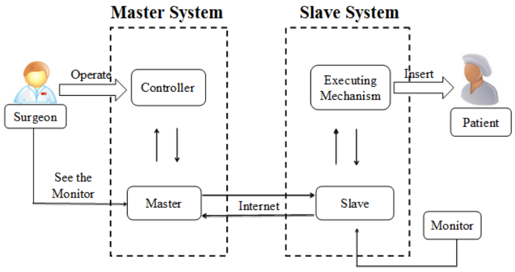


Fig.1 The general structure of Internet based tele-surgical system

In reference [5], we have already finished this model in two dimensional models. Therefore, the purpose of this paper is to present a new method based on image-processing technology to efficiently reduce the transmission time of visual feedback in three dimensional model and make easier to control the time difference between haptic, control signals and image information due to reduce the amount of communication data of image information. Also, a remote transmission experiment of visual feedback was conducted to show that the proposed prototype made a better performance improvement for Internet-based transmission with delays, which was conducted between Beijing, China and Takamatsu, Japan. The aims of the experiment were to examine the comparison before and after applying the proposed architecture.

This paper is organized as follows: In next section, the method of reducing the transmission of image information is presented. Experiments to verify our method are described in section III. Finally, a brief conclusion and future work section is presented in Section IV.

II. METHOD AND IMPLEMENTATION

Obviously, time delay of the transmission of visual feedback becomes an increasingly crucial problem encountered in Internet-based tele-operative surgery. As for our robotic catheter operating system, time delay can be defined as equation 1 shown:

$$T_{total} = T_{transmission1} + T_{response} + T_{tansmission2} \qquad (1)$$

$T_{transmission1}$ means the transmission delay of control signal from master system to slave system and $T_{response}$ represents the response time of slave system and $T_{tansmission2}$ presents the transmission delay of visual or haptic feedback from slave system back to master system. We mainly focused on the method to solve the delay of visual feedback by reducing the amount of data transmission in this paper.

The whole structure of prototype is described as **Fig. 2** shows. Two cameras are used to capture the images of catheter at the same time and two images are sent to image processor module to get the three dimensional coordinates of catheter. Next, these three dimensional coordinates are transmitted to operation site through the Internet. Then, at operation site, three dimensional coordinates received from surgery site are re-constructed as the visual feedback in real time. According to the reconstructed catheter model at master system, doctors decide to do what the kind of operation.

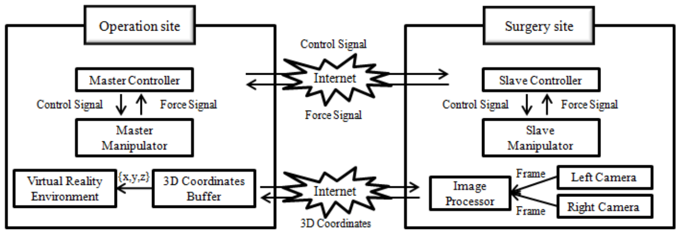


Fig.2 The structure of our Internet-based tele-operative surgical system

In this proposed prototype, image processor plays an important role, which consists of 5 steps to calculate the three-dimensional coordinates of catheter in World Coordinate System, as the **Fig. 4** shows.

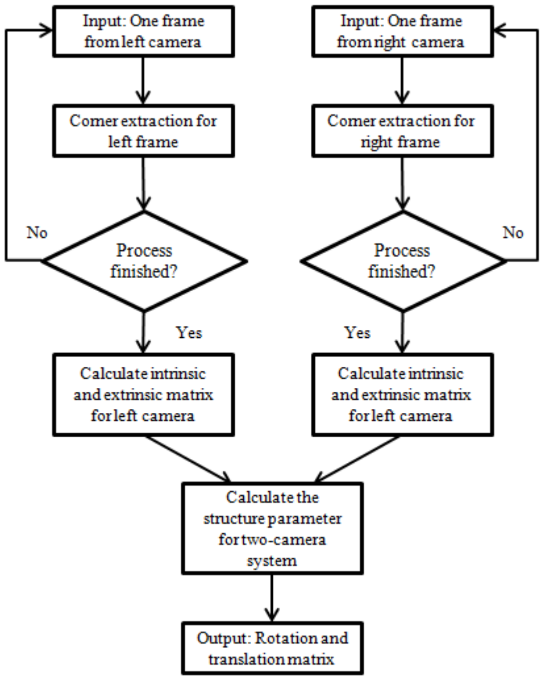


Fig.3 Procedures of two-camera calibration

A. Two-camera System Calibration

During the calibration procedure, there are three kinds of coordinate system, image coordinate system, camera coordinate system and world coordinate system. The relationship between image coordinate system [u, v, 1] and camera coordinate system [X_c, Y_c, Z_c] is calculated as equation 2 shown:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \frac{1}{Z_c} \begin{bmatrix} \frac{1}{k} & 0 & u_0 \\ 0 & \frac{1}{l} & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f & -f\cot\theta & 0 & 0 \\ 0 & f/\sin\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix}$$

$$= \frac{1}{Z_c}\begin{bmatrix} f/k & -(f/k)\cot\theta & 0 & 0 \\ 0 & f/l\sin\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \frac{1}{Z_c} AP_c \quad (2)$$

where the size of pixel is k * l and its unit is millimetre, f is focal length and θ is the angle between X, Y and Z axis. Generally, θ is similar to 90^o. However, in our case, we do not consider it as 90^o in order to get a higher precision. Due to the fact that matrix A concludes all the parameters of a camera (k, l, u0, v0, f, θ), it is the intrinsic matrix of a camera and we calculate it every time before experiments in order to improve the precision.

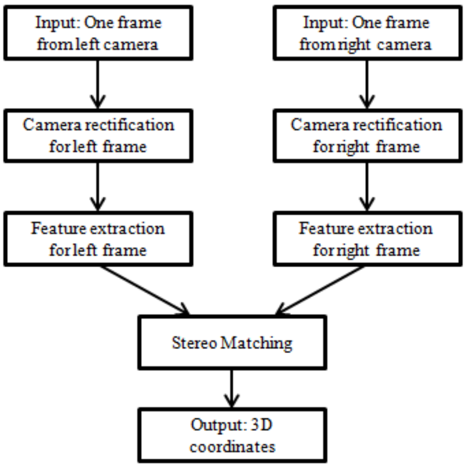


Fig.4 Procedures of images processor module

Furthermore, the correlation between camera coordinate system and world coordinate system is built. R is a rotation matrix and t is a translate vector. Based on matrix R and vector t, the position information between left and right camera are obtained.

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} R_{3\times3} & T_{3\times1} \\ 0^T & 1 \end{bmatrix}\begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \quad (3)$$

Therefore, the purpose of two-camera calibration is to calculate the intrinsic and extrinsic matrix of two cameras in order to build a corresponding relationship between three-dimensional world coordinates and two-dimensional image coordinates.

To find the intrinsic and extrinsic matrix, each of the cameras is calibrated using the Zhang's method [17]. This method is simple and mainly based on different nonparallel views of a planar pattern [18] (e.g., a chessboard as Fig.5 shown).

The algorithm shown in **Fig. 3** is used for computing intrinsic and extrinsic parameters is as follows: 1) capture two frames of a 6 × 8 black and white planar chessboard pattern (Fig.5) from left and right cameras at the same time; 2) detect the corners of the pattern in each of the frames; 3) find a homograph for all points in the set of images, where a homograph is a matrix of perspective transforms between the calibration pattern plane and the camera view plane; 4) initialize intrinsic parameters from the perspective transforms; 5) find extrinsic parameters for each image of the pattern; and 6) minimize the error of the projection points with all the parameters using a maximum likelihood algorithm.

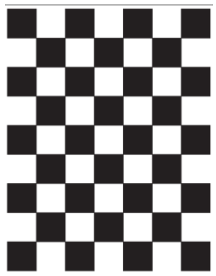


Fig.5 a chessboard used for two-camera calibration

B. Two-camera System Rectification

In terms of two-camera system, epipolar geometric constraints are used to shorten stereo matching time and improve matching precision. **Fig. 5** shows the epipolar geometry of two cameras system, where the line between C1 and C2 is baseline and e1, e2 are epipolar points for left and right camera respectively. Also, *l1*and *l2* are epipolar lines. According to the epipolar geometric constraints of two-cameras system, for any pixel pl in the left image, its correspondence must lie on the epipolar line in the right image.

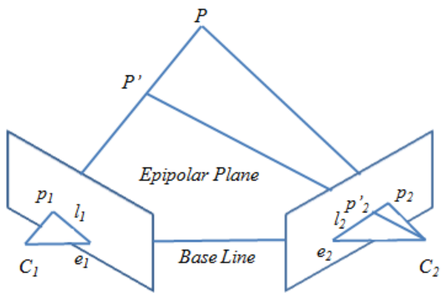


Fig.6 Imaging model of two cameras system

Furthermore, in order to promote the computing speed, we used a perspective transformation to set the epipolar points move to infinite distance, thereby epipolar lines becoming to groups of parallel lines. Next, a similarity transform is applied to transform the parallel epipolar lines to parallel to horizontal axis of image coordinates. Finally, a shear transformation is performed in two frames from left and right cameras in order to make image distortion in horizontal direction reach minimum value.

C. Feature Extraction and Stereo Matching

In order to extract the shape of a catheter, some red instrument markers is attached to a 2mm diameter catheter and every two red markers are deployed with 1 centimeter space distance, and specific distribution of markers has been shown in **Fig. 7**. Furthermore, the length of a real catheter is about 50 centimeters, thus 50 red markers are required to represent the shape of a catheter. In addition, the markers are extremely thin and cannot enlarge the diameter of a real catheter and lubricants are attached the catheter to decrease the frictional resistance whether in an experiment or a real vascular interventional surgery.

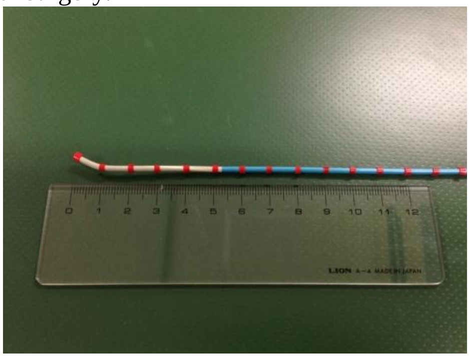


Fig.7. The red markers attached on a 2mm diameter catheter

To recover 3D coordinates of every marker on a catheter, we first need to extract corresponding feature points (red markers), and then match feature points from two cameras to form identical points. In order to find the red markers in two rectified images from left and right cameras captured at the same time, the images are firstly converted from RGB format to HSV format. Then, the red markers are separated from the images by setting a range of values of hue and saturation. That is, a lower threshold and an upper threshold value of hue and saturation are used to extract red markers from background. Next, an erosion and dilation algorithm is adopted to remove the noise generated by experimental environment. Finally, circumcircles are calculated for every red marker and we take the coordinates of the centre of each circumcircle as its 2D image coordinates.

Due to the fact that the image rows between the two cameras are aligned after rectification, the matching points will locate in identical horizontal direction and have the same value of vertical coordinates in two frames captured by left and right cameras respectively. And there are the same numbers of red markers in left and right images. Thus, for a red marker in left image, its corresponding marker must lie in almost the same horizontal line in right image. That is, the two red markers in two images have approximately the same value of vertical coordinate.

D. 3D Coordinates Reconstruction

As for the rectified images captured from left and right camera, there is a fast algorithm to rebuild three-dimensional coordinates of catheter due to the fact that the pair of left and right images can be considered as two images captured by two parallel cameras.

Assumed that $p1=(u1\ v1\ 1)^T$ and $p2=(u2\ v1\ 1)^T$ are a pair of matched points. Also, the coordinates value of point P in world coordinates defined by p1 and p2 from left camera perspective view is: $P = (X, Y, Z, 1)^T$ and $P = (X\text{-}b, Y, Z, 1)^T$ from right camera perspective view, where b is the baseline between two cameras. Due to d = u1 - u2 as the disparity value, (X, Y, Z) can be calculated according to the three equations above:

$$\begin{cases} X = \frac{b}{d}\left[u_1 - u_0 + \frac{(v_1 - v_0) l \cot\theta}{k}\right] \\ Y = \frac{(v_1 - v_0) l b \sin\theta}{kd} \\ Z = \frac{fb}{kd} \end{cases} \tag{5}$$

IV. EXPERIMENTAL RESULTS

In order to testify the proposed prototype in this paper, we designed a series of experiments to test the accuracy of the reconstruction algorithm and compare the transmission time visual feedback from master system to slave system before and after applying the proposed architecture. First of all, the Inter net-based catheter operating system is introduce, based on which we did the experiments

A. Internet-based Catheter Operating System

The Internet-based robotic catheter operating system consists of two parts, a master system and a slave system. And two systems are connected by Internet.

The mechanical designs of master system and slave system [19]-[23] are shown in **Fig.8-9.**

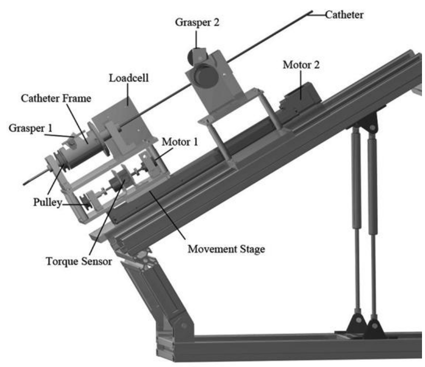


Fig.8 The slave system of Internet-based tele-operatives catheter system

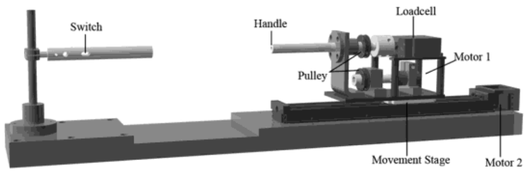


Fig.9 The master system of Internet-based tele-operatives catheter system

At operation site, surgeons see the reconstructed catheter model and operate the handle of master manipulator to do the operation of insertion and rotation. At the same time, controlling instructions are transmitted to surgery site. According to the controlling signals from master system, slave manipulator can insert or rotate catheter and the status of catheter will be detect by two-camera system.

B. Experiments on Two-camera system Calibration

We used a chessboard shown in **Fig.5** to calculate the intrinsic and extrinsic matrix and register the two cameras to the universal coordinates.

The distortion parameters k_1, k_2, p_1, p_2 and the intrinsic parameters f_u, f_v, c_u, c_v, α, resulting from this algorithm for each of the cameras are listed in Table I and Table II, respectively. The accuracy of this calibration method has been reported to be 0.7197 pixels.

TABLE I
Distortion Parameters For Left and Right Cameras

	k_1	k_2	p_1	p_2
Left Camera	-0.197	0.628	0	0
Right Camera	-0.2443	0.8192	0	0

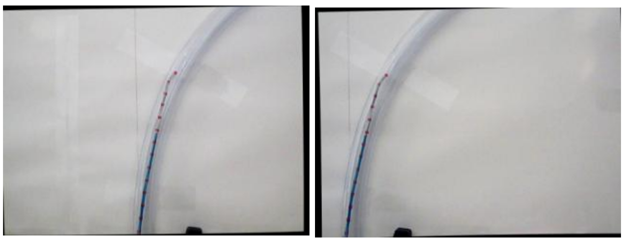
TABLE II
Intrinsic Parameters for Left and Right Cameras

	f_u	f_v	α	c_u	c_v
Left Camera	991.74	991.74	0	319.5	239.5
Right Camera	1028	1028	0	319.5	239.5

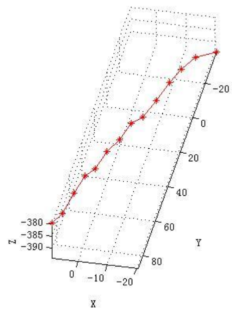
C. *Experiments on Three-dimensional Reconstruction*

The reconstruction algorithm has been introduced in part II of this paper. Here are two experiments to show the results using our proposed methods.

Fig. 10(a) and **Fig. 10(b)** show the extracted real catheter in world space from left and right camera and **Fig. 10(c)** and show the corresponding coordinates of red markers. In additon, another experiment is performed as **Fig. 12** shown.

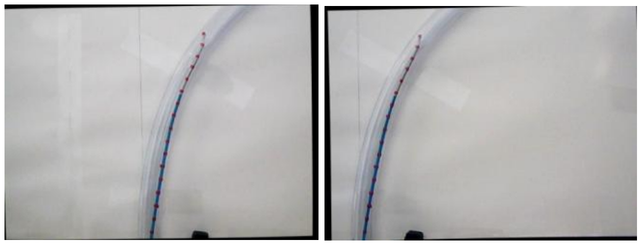


(a) Real catheter in left camera (b) Real catheter in right camera

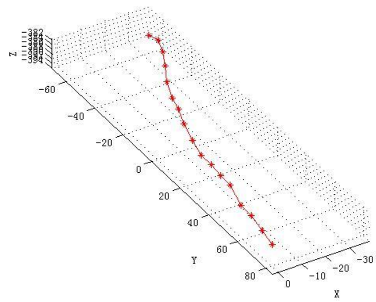


(c) Coordinates of red markers

Fig. 10 Results of experiment I



(a) Real catheter in left camera (b) Real catheter in right camera



(c) Coordinates of red markers

Fig. 11 Results of experiment I

D. *Remote Transmission Experiments between China and Japan*

Based on the proposed method, the visual feedback is changed from image transmission to coordinates extraction and transmission. We conducted ten experiments to compare the transmission time before and after applying the proposed architecture. We delivered 100 pieces of images captured in our remote expriments and their corresponding coordinates rebuit based on our method from Takamatsu, Japan to Chengdu and Shanghai, China. The sizes of each image and its coordinates files are approximately 91,689 Bytes and 18,324 Bytes, respectively. The left bar in **Fig.12** and **Fig.13** shows transmission time of images and the other bar shows the sum time of coordinates extraction and coordinates transmission. The transmission time can be reduced efficiently.

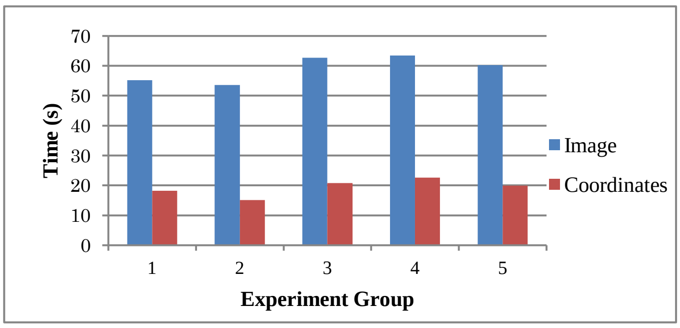


Fig.12 Remote transmission experiments from Takamatsu to Chengdu

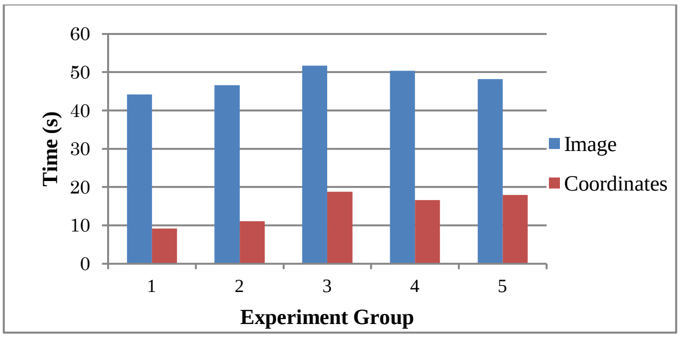


Fig.13 Remote transmission experiments from Takamatsu to Shanghai

V. CONCLUSION

In this paper, we applied the two-camera system to detect the status of catheter and transform it to three-dimensional coordinates due to image-processing algorithm. The three-dimensional coordinates are transmitted to master system instead of image information and reconstructed in virtual reality environment as the visual feedback from slave system. The transmission time of visual feedback is effectively reduced due to the significant reduction of data volume. In experimental part, we did a remote transmission compared the transmission time before and after using the proposed prototype.

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